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The nature of (sub)millimetre galaxies in hierarchical models

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Abstract. We present a hierarchical galaxy formation model which can account for the number counts of sources detected through their emission at sub-millimetre wavelengths. The first stage in our approach is an *ab initio* calculation of the star formation histories for a representative sample of galaxies, which is carried out using the semi-analytical galaxy formation model `GALFORM`. These star formation histories are then input into the spectro-photometric code `GRASIL`, to produce a spectral energy distribution for each galaxy. Dust extinction and emission are treated self consistently in our model, without having to resort to ad-hoc assumptions about the amount of attenuation by dust or the temperature at which the dust radiates. We argue that it is necessary to modify the form of the stellar initial mass function in starbursts in order to match the observed number of sub-mm sources, if we are to retain the previous good matches enjoyed between observations and model predictions in the local universe. We also list some other observational tests that have been passed by our model.

1. Introduction

The first few years of the millennium have seen increased support assembled for the hierarchical structure formation paradigm (Spergel et al. 2003). In this model, small ripples in the density of the primordial universe are amplified by the force of gravity acting over billions of years. The most successful model, a universe in which cold dark matter outweighs baryonic matter and in which the rate of expansion is accelerating due to a dynamically dominant dark energy component, agrees spectacularly well with the latest measurements of the primordial spectrum of density perturbations, as shown in Fig. 1.

Physical models of galaxy formation in a hierarchical universe are also reaching maturity. The roots of modern-day "semi-analytical" galaxy formation models actually predate the cold dark matter cosmology and took hold in the 1970s, with the papers by Press & Schechter (1974) and White & Rees (1978). These papers set out the basic ideas which underpin the approach, namely that galax-

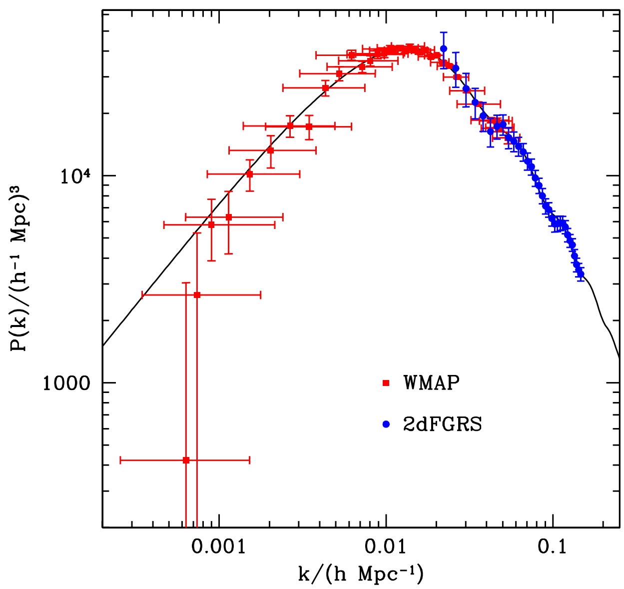

Figure 1. The power spectrum of temperature fluctuations in the cosmic microwave background radiation (the first year WMAP data; Hinshaw et al. 2003) plotted on the same scale as the power spectrum of galaxy clustering measured from the two-degree field galaxy redshift survey by Cole et al. (2005). Figure courtesy of Ariel Sanchez, based on results from Sanchez et al. (2006).

ies form by the radiative cooling of baryons inside dark matter haloes which were assembled by a merging process driven by gravitational instability. The 1990s saw the first detailed calculations based on these ideas which established the validity of the approach (White & Frenk 1991; Kauffmann, White & Charlot 1993; Lacey et al. 1993; Cole et al. 1994). These models are now firmly established as a powerful tool which can generate testable predictions, connecting hierarchical clustering cosmologies to observations of the galaxy population at different epochs in the history of the universe.

Now that the parameter space which defines the background cosmology is shrinking (see for example Sanchez et al. 2006), semi-analytical models of galaxy formation are entering a new phase. Coupled with the explosion of observational data available for galaxies at high redshift, the focus is shifting towards a critical assessment of the physics implemented in the models. The modular nature of the models and their speed means that different prescriptions can be tested for a particular physical process. The ongoing efforts to improve the modelling of the various phenomena involved in the galaxy formation process are inevitable, given their complexity and our lack of detailed understanding of the relevant physics.

The problem of matching the bright end of the local field galaxy luminosity function provides a good illustration of this point (Benson et al. 2003). The first generation of semi-analytical models had little problem in matching the

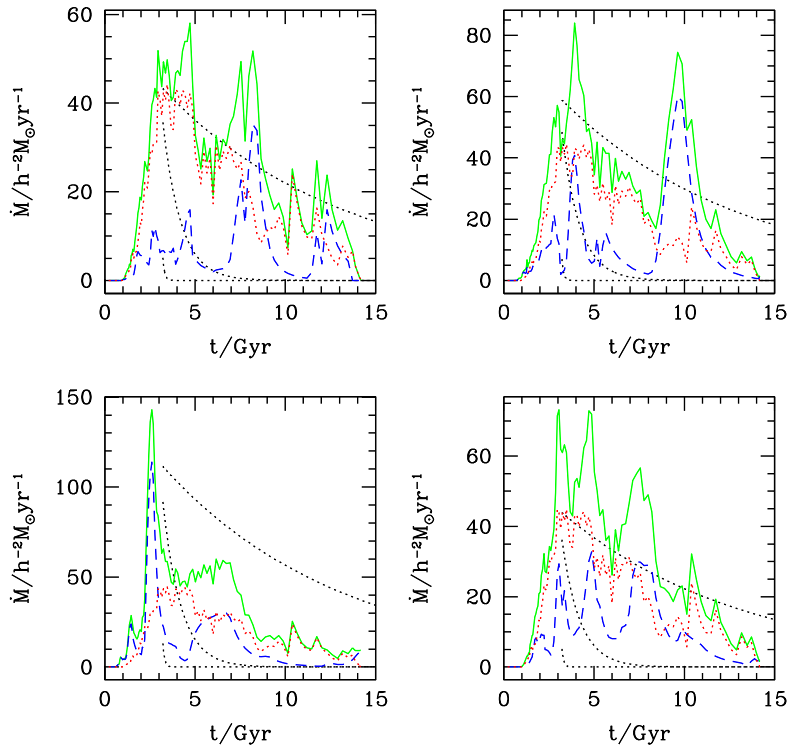

Figure 2. The star formation histories for four massive galaxies, as predicted by the `GALFORM` model, plotted as a function of the age of the model universe. The total star formation rate (solid line) takes into account the quiescent star formation in the progenitors of the present day object (dashed line), and includes starbursts triggered by galaxy mergers (dotted line). The smooth dotted curves show simple exponential star formation laws for comparison; these star formation histories start when the universe was 3 Gyr old and have e-fold times of 0.1, 1 and 10 Gyr.

exponential break observed in galaxy luminosity function. Today, modellers find this a more challenging task for two reasons: (i) A shift in the favoured cosmological model. Today, the "standard" cold dark matter model has a matter density parameter less than one third of the critical density (Sanchez et al. 2006). Structures tend to form earlier in a dark energy dominated universe, so, coupled with the slightly older age for the universe in this cosmology, more massive haloes have been able to cool gas for a longer period than would have been the case in a universe with the critical density in matter. This leads to more gas cooling in these haloes. This problem is exacerbated by the tighter observational constraints on the baryon density, which typically result in higher baryon densities being input into the models than would have been used in earlier calculations. (ii) The luminosity function is not being considered in isolation. The continued development of the models now means that they are able to predict a much wider range of galaxy properties than was possible in the early days. This increased sophistication actually makes it more difficult to match one

particular observation because other galaxy properties can be adversely affected by parameter changes.

The attempt to find a solution to the problem of matching the sharpness of the observed break of the bright end of the luminosity function has led to a revision of the treatments of gas cooling and feedback in massive haloes used in the models (e.g. Benson et al. 2003; Bower et al. 2006; Croton et al. 2006; de Lucia et al. 2006). While some of our more conservative colleagues view such changes as sufficient grounds on which to dismiss the semi-analytical approach altogether, what we are witnessing is simply the application of the scientific method; when a model prediction is found to be incorrect, this shows that an ingredient in the scenario is either modelled incorrectly or is missing altogether. The resolution of the discrepancy leads to a new model in which our understanding of galaxy formation has been advanced. Now that the utility of this approach has gained general acceptance, we should welcome conflict between observations and theoretical predictions, as this will drive future progress in the models.

In this article, we deal with another area in which the models have faced a stern challenge; matching the abundance of high redshift galaxies detected through their dust emission in the sub-mm. At first sight, the galaxies seen with the `SCUBA` instrument at 850 microns appeared to be massive galaxies at high redshift, with star formation rates approaching $1000 M_{\odot} yr^{-1}$ (Smail et al. 1997). Such objects would dominate the star formation in the early Universe, dwarfing the contribution of galaxies seen in the rest-frame ultraviolet (Hughes et al. 1998; Barger et al. 1998). Our solution to this problem is controversial, but spawns a number of testable predictions. On the whole these predictions agree remarkably well with observations, as we will discuss. In § 2, we give a brief overview of our model of galaxy formation. Our treatment of the impact of dust on the spectral energy distribution of our model galaxies is a novel apsect of our model and is described in § 3. We present the main results of interest to the participants of this workshop in § 4. Further tests of the model are listed in § 5 along with our conclusions.

2. The galaxy formation model

We use the semi-analytical model `GALFORM`; the content of the model and the philosophy behind it are set out in detail in Cole et al. (2000). Important revisions to the basic model are described in Benson et al. (2002, 2003). Our solution to the problem of accommodating the number counts of `SCUBA` sources in the cold dark matter model is explained in Baugh et al. (2005).

In summary, the aim of `GALFORM` is to carry out an *ab initio* calculation of the formation and evolution of galaxies, in a background cosmology in which structures grow hierarchically. The physical ingredients considered in the model include: (i) The formation of dark matter haloes through mergers and accretion of material. (ii) The collapse of baryons into the gravitational potential wells of dark matter haloes. (iii) The radiative cooling of gas that is shock heated during infall into the dark halo. (iv) The formation of a rotationally supported disk of cold gas. (v) The formation of stars from the cold gas. (vi) The injection of energy into the interstellar medium, through supernova explosions or the ac-

cretion of material onto a supermassive black hole. (vii) The chemical evolution of the interstellar medium, stars and the hot gas. (viii) The merger of galaxies following the merger of their host dark matter haloes, due to dynamical friction. (ix) The formation of spheroids during mergers due to the rearrangement of pre-existing stars (i.e. the disk and bulge of the progenitor galaxies) and the formation of stars in a burst. (x) The construction of a composite stellar population for each galaxy, yielding a spectral energy distribution, including the effects of dust extinction, a point to which we shall return in more detail later on in this section.

Four examples of the star formation histories predicted by `GALFORM` are shown in Fig. 2. The cases shown are massive galaxies at the present day. The star formation history of a galaxy is constructed by considering the quiescent star formation in all of its progenitors and all the bursts of star formation triggered by galaxy mergers. A common *assumption* for the star formation history of a galaxy made in many other models is that stars form with an exponentially declining rate; some examples of such histories are marked on each panel with illustrative e-folding times. The star formation histories *predicted* by `GALFORM` are quite different from the simple exponential form.

3. The effect of dust on the spectral energy distribution

In order to make predictions for the sub-mm emission from galaxies, we need to take into account the effect of dust on the spectral energy distribution of galaxies. Previous work in this area has either employed template spectral energy distributions based on local galaxies (e.g. Blain et al. 1999; Devriendt & Guiderdoni 2000) or has treated the temperature of the dust, $T_{\rm d}$, as a free parameter (e.g. Kaviani, Haehnelt & Kauffmann 2003). The dust luminosity per unit frequency at long wavelengths scales as $T_{\rm d}^{-5}$ for a given bolometric dust luminosity, for a standard assumption about the emissivity of the dust. Given this strong dependence of luminosity on $T_{\rm d}$, it would appear trivial to match the observed sub-mm counts by simply making a modest tweak to the dust temperature. Unfortunately, such a model is unphysical. The dust temperature should be set by requiring that the dust grains be in thermal equilibrium, with a balance between radiative heating and cooling. With this criteria met, the dust luminosity per unit frequency depends rather less dramatically upon the bolometric luminosity and the dust mass; significant changes to these properties are required to change the dust luminosity (see Baugh et al. 2005 for a discussion).

An important feature of our model is a physically consistent treatment of the extinction of starlight by dust and the reprocessing of this energy at longer wavelengths. This is achieved by using the `GRASIL` spectro-photometric model introduced by Silva et al. (1998). `GRASIL` computes the emission from both the stars and dust in a galaxy, based on the star formation and metal enrichment histories predicted by the semi-analytical model (Granato et al. 2000). `GRASIL` includes radiative transfer through a two-phase dust medium, with a diffuse component and giant molecular clouds, and a distribution of dust grain sizes. Stars are assumed to form inside the clouds and then gradually migrate. The output from `GRASIL` is the galaxy SED from the far-UV to the sub-mm.

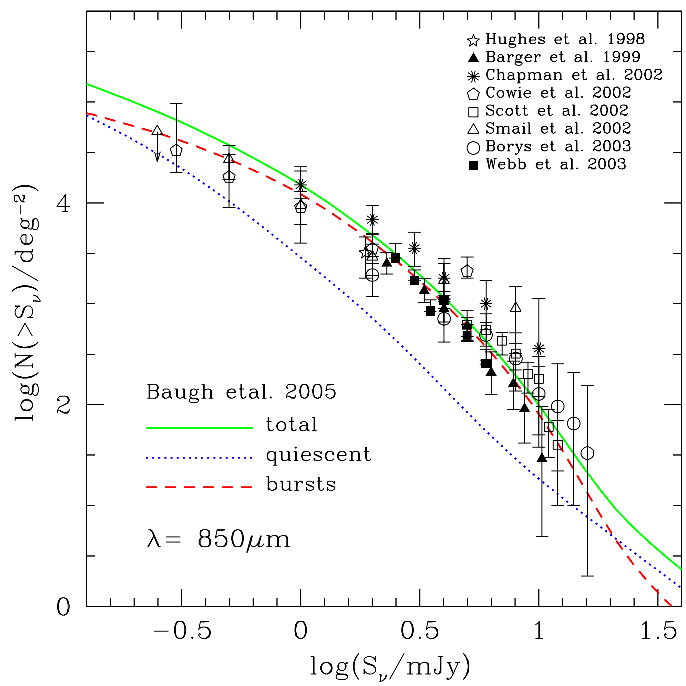

Figure 3. The cumulative number counts of galaxies at 850 microns predicted by the Baugh et al. (2005) model, compared with a compilation of observational estimates, as indicated by the legend. The solid curve shows the total number counts, the dashed curve the contribution from galaxies which are undergoing a galaxy merger induced starburst and the dotted curve shows the counts from galaxies that are forming stars quiescently in galactic discs.

4. Results

Previous attempts to match the observed counts of sub-mm sources using the combined `GALFORM` and `GRASIL` machinery, whilst retaining the successes of the models at other redshifts, were unsuccessful, failing to match the counts by over an order of magnitude (see Baugh et al. 2005). The are two principle reasons for the increased counts of sub-mm galaxies in the model introduced by Baugh et al, as shown by Fig. 3. Firstly, more star formation takes place in starbursts than in earlier models. There are two reasons for this. In the new model, the timescale for quiescent star formation is independent of redshift, instead of scaling with the dynamical time of the galaxy as in the fiducial model of Cole et al. (2000). High redshift disks consequently have larger gas fractions than before, resulting in gas rich starbursts at early epochs. In addition, in the new model, a burst can be triggered by the accretion of a satellite galaxy which brings in a modest amount of mass. Such a collision is assumed to leave the stellar disk of the primary galaxy intact, but induces instabilities in the cold gas present, driving it to the centre of the galaxy, where it takes part in a burst. Secondly, we assume

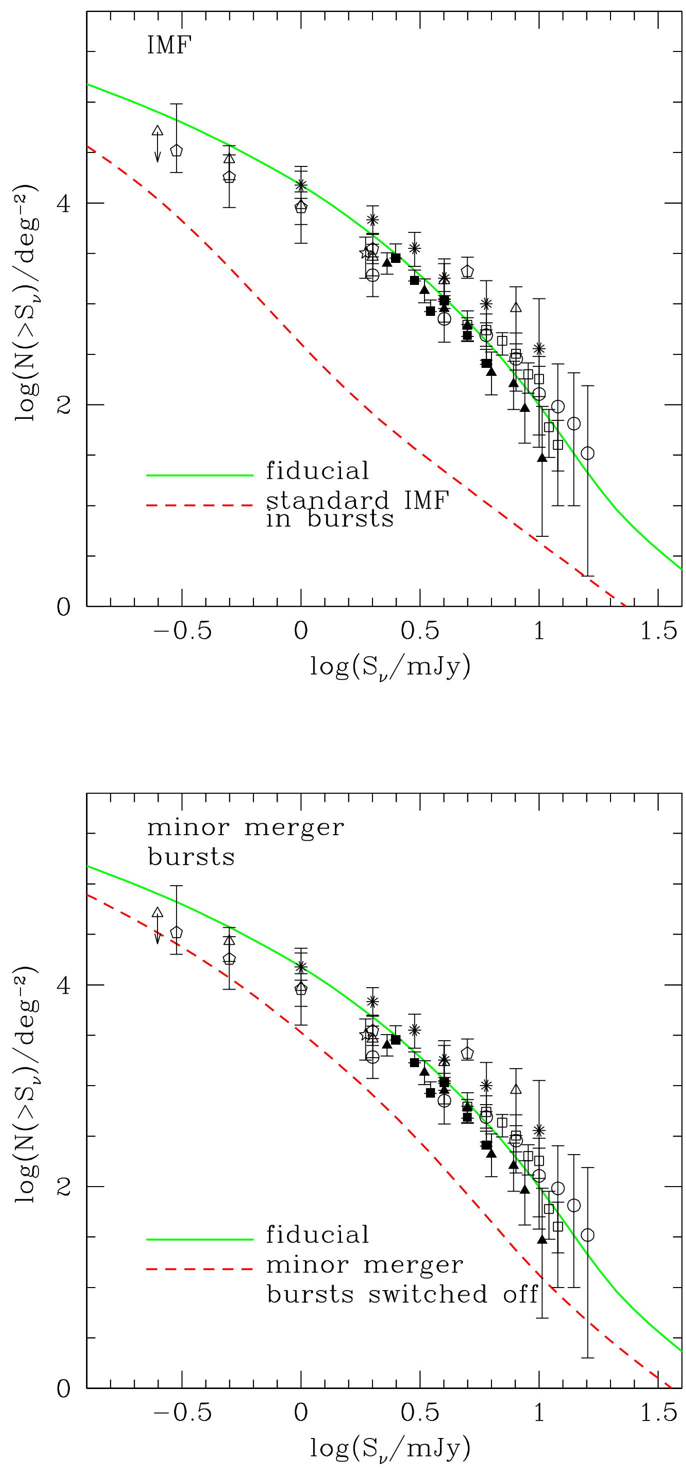

Figure 4. The impact on the predicted number counts of switching off key ingredients of the model. The fiducial model from Baugh et al. (2005) is shown by the solid line; as Fig 3 shows this model matches the observed counts remarkably well. In the upper panel, the dashed line shows the predicted counts if we adopt a standard IMF for star formation in merger induced bursts, rather than the flat IMF used in the fiducial model. In the bottom panel, the dashed curve shows how the counts change if starbursts triggered by minor merger (i.e. when a gas rich disk is hit by a small satellite) are

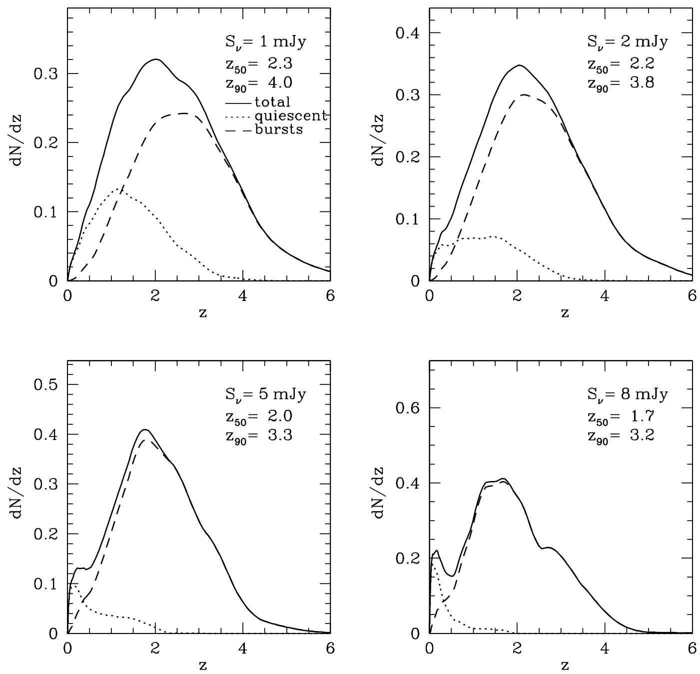

Figure 5. The predicted redshift distribution at a series of 850 micron fluxes (as indicated in the key). The solid lines shows the redshift distribution of all galaxies, the dashed lines shows ongoing bursts and the dotted lines show galaxies which are forming star quiescently. The median redshift (z_{50}) and the redshift below with 90% of galaxies are predicted to lie (z_{90}) are also given on each panel.

that star formation induced by mergers produces stars with a flat initial mass function (IMF). With a larger proportion of high mass stars, the total energy radiated in the ultra-violet per units mass of stars produced is increased, thus increasing the amount of radiation heating the dust. Moreover, the flat IMF produces a higher yield of metals than a standard, solar neighbourhood IMF, which means more dust.

The impact of these two ingredients is readily apparent from the comparisons presented in Fig 4. One of the beauties of semi-analytcal modelling is that certain aspects of the model can be switched on and off in order to assess their impact on the predictions. These comparisons show that the assumption of a flat IMF in starbursts is the main factor responsible for the model reproducing the observed counts. The model predictions for the redshift distribution of sub-mm sources are shown in Fig. 5. At bright fluxes, the predictions are in good agreement with the median redshift determined by Chapman et al. (2003).

5. Conclusions

The assumption of a flat IMF in starbursts is undoubtedly controversial. It is therefore important to explore the predictions of the model in detail, to find other evidence in support of this choice. The successes of the our new model include:

- The reproduction of the properties of the local galaxy population, such as the optical and near infrared luminosity functions and the distribution of disk scalelengths. This is the first hurdle that any realistic model of galaxy formation should overcome. Not only does this undermine any claims of chicanery when changing model parameters, it also permits a meaningful discussion of the descendants of high redshift galaxies.

- The recovery of the luminosity function of Lyman break galaxies at $z = 3$ and $z = 4$, with a realistic degree of dust extinction in the rest frame UV, computed by tracking the chemical evolution of the model galaxies and calculating the sizes of the disk and bulge components.

- Nagashima et al. (2005a) show that the model with a flat IMF reproduces the observed abundances of elements in the hot gas in clusters.

- Nagashima et al. (2005b) applied the same model to the calculation of element abundances in elliptical galaxies and again found better agreement with the model in which starbursts have a flat IMF.

- Le Delliou et al. (2005, 2006) computed the abundance of Lyman-alpha emitters using `GALFORM`. The Baugh et al. model gives a somewhat better match to the shape of the observed counts than a model with a standard IMF.

Granato et al. (2004) present an alternative model in which they consider the evolution of quasars and spheroids. These authors find that they can explain the number counts of sub-mm galaxies without using a non-standard IMF, by using different feedback and gas cooling prescriptions from those employed in the model of Baugh et al. (2005). While it is not clear that these recipes would still work in a fully fledged semi-analytical model (Granato et al. do not follow galactic disks nor do they consider mergers between galaxies or between haloes), it will be interesting to see if the new generation of semi-analytical models with modified cooling and feedback prescriptions in massive haloes can reproduce the number counts of dusty galaxies with a standard choice of IMF (Croton et al. 2006; Bower et al. 2006).

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